Journal of African Earth Sciences 100 (2014) 60–69

Contents lists available at ScienceDirect

Journal of African Earth Sciences

journal homepage: www.elsevier.com/locate/jafrearsci

Impact of wellsite biostratigraphy on exploration drilling in the deepwater offshore Nigeria

Suyi Lawrence Fadiya *

Department of Geology, Obafemi Awolowo University, Ile-Ife, Nigeria

ARTICLE INFO

Article history:
Received 29 March 2013
Received in revised form 4 June 2014
Accepted 9 June 2014
Available online 26 June 2014

Keywords:
Wellsite
Biostratigraphy
Exploration
Calcareous nannofossils
Deepwater
Niger Delta

ABSTRACT

The application of wellsite biostratigraphic technique has aided the reconstruction of the subsurface geology in the Nigerian deepwater region. It has further aided decision making during drilling operations including the planning of well paths. Critical decisions regarding casing setting, coring point selection, overpressure zone determination and total depth picks, are easily achieved through confirmation of well prognosis and correlation to offset wells. This technique is very important in the tectonically active Nigerian deepwater region which is characterized by varying degrees of both syn-depositional and post-depositional deformation. Accurate interpretation of basin architecture, lateral variation and facies change is required before drilling. Confirmation of well prognosis during drilling operation is equally important.

It has been proved that wellsite biostratigraphic technique helps to "get it right at first" when integrated with the traditional lithologic description, log signature correlation and seismic profile interpretations. The modern and rapid processing technique of calcareous nannofossil, for instance, provides 'real time' result for the exploration team for confirmation of, or adjustment to, the drilling program. The attendant contribution in saved time, cost and safe and successful drilling operation makes the technique beneficial for all operators.

This paper presents practical experience of wellsite biostratigraphy application in three oil prolific Nigerian deepwater regions: the Niger Delta, Joint Development zone of Nigeria/Sao Tome and Principe area (JDZ) and Benin (Dahomey) Basin.

1. Introduction

In drilling any well, the planning team puts priority on saving time and consequently money. This is vital even on onshore rigs where the cost of drilling is less expensive. Deepwater drilling is very expensive, bearing in mind the cost of drillship, personnel conveyance and supply boats. The daily rates of specialized services in sinking a well in the deepwater environment are generally in the tune of hundreds of thousands of dollars. With this in mind, every minute matters a lot to all operators who want to ensure that as much time as possible is saved.

Besides planning of logistics and the drilling program proper, it is important to put together the various aspects of exploration that will ensure that you 'get it right at first'. When targets are missed, the drilling process is either repeated in the form of sidetracks or the data obtained managed with greater risks, with both situations having cost implications. If the target is missed and an attempt to make any correction involves pulling out of hole, the loss could run into hundreds of thousands of dollars. Besides, adequate prediction is required to ensure safety of lives of rig personnel and marine lives most especially in areas with overpressured shales, which is a common phenomenon in the Niger Delta.

The Niger Delta area and the adjoining basins are situated in a tectonically active region and are subjected to both syn-depositional and post-depositional deformation. The Niger Delta basin has witnessed varying degrees of both syn- and post-depositional deformation (Fig. 1) with gravity tectonism as a primary deformation process (Ajakaiye and Bally, 2002). The principle of original horizontality is disturbed by tectonism in many areas. Thus, horizontally laid sediments are distorted in such an unpredictable manner that their succession can only be interpreted using the most modern exploration techniques. The Toe Thrust belt shows the extent of deformation in the Niger Delta deeper waters. Besides tectonic activities, basin architecture, lateral variation and facies changes in deposited sediments need to be accurately interpreted. Else, the same lateral sequence of sand grading into shale could be mistaken for different horizons.

Two discrete evidences of post-faulting deformation mechanisms have been documented by Maloney et al. (2010) with the

* Tel.: +234 80333 20230.
E-mail addresses: fadiyalawrence@yahoo.co.uk, slfadiya@oauife.edu.ng

http://dx.doi.org/10.1016/j.jafrearsci.2014.06.009
1464-343X/© 2014 The Authors. Published by Elsevier Ltd.

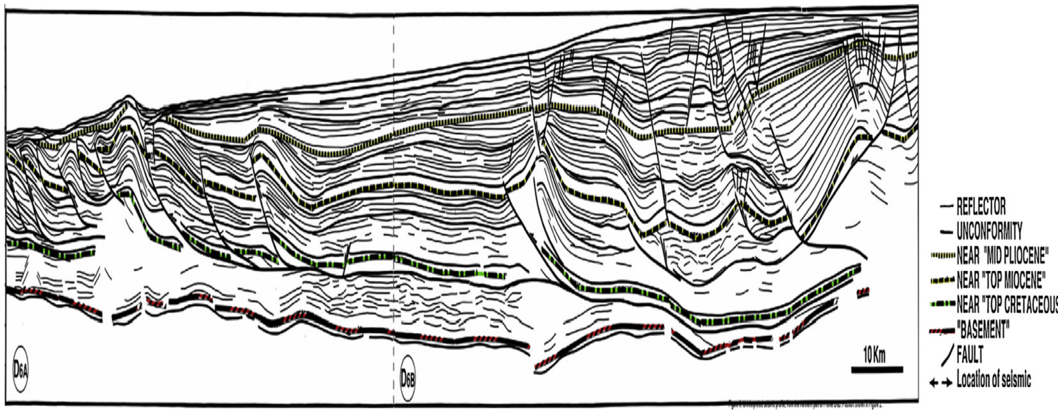

Fig. 1. Line drawing of seismic profile D6A and D6B in the Toe-Thrust zone of the Niger Delta (adapted from Ajakaiye and Bally, 2002).

use of two- and three-dimensional seismic reflection data from the deep-water Niger Delta fold and thrust belt mechanisms. They interpreted an early phase of thrust-propagation folding followed by folding caused by thickness changes within the basal shale detachment unit. The later phase of folding was said to have been caused by a lateral redistribution of the strata within the basal detachment unit. Corredor et al. (2005) used the patterns of growth, sedimentation, fold shapes, fault plane seismic reflections and combined conventional and shear fault-bend folding theories to describe and model the structural styles and kinematics of the fault related folds and imbricate thrust systems that compose the two large fold and thrust belts in the Deep-water Niger Delta. Leduc et al. (2012) used two- and three-dimensional seismic data to describe the structural geology of the lateral margin of a deep-water delta lobe within the Niger Delta that has undergone basin-ward, gravitationally driven translation. They referred to this region as "lateral strike-slip domain".

Whatever mechanism is responsible for the structural complexities described above, there is the need to resolve the distorted sequences and place them sequentially to aid exploration activities. Biostratigraphy plays a big role as one of the techniques in the subsurface interpretation of the sequences most especially at the point of drilling.

The use of seismic method with its advancement up to the 4-D is an important tool in predicting the subsurface geology. Consequently, pre-drilling interpretation is made of the subsurface using all available techniques especially seismic. Where available, projections from offset/adjacent wells' data are made. Through this, depth to targets, overpressured zones and major horizons are calculated. From these, the drilling program is drawn and the different operations outlined. Casing depths, primary and secondary targets depths are estimated and coring point depths are projected. It is also possible to estimate the depth to the overpressured zone where such is suspected and to predict the well's total depth (Ramirez et al., 2005).

It is equally important to ensure that during drilling operations, the prognosis falls in place and that discrepancies are located where they occur so that adjustments can be made to the drilling program. Traditionally, results of lithologic description, log signatures and seismic are employed to effect these. These results are correlated to the point of reference which could be an offset well. This method has proved to be very effective. Occasional mismatching, however, occurs. As drilling in the offshore requires a degree of precision that will ensure cost saving and eliminate the risk of loss of lives, integrating all available exploration techniques is important.

While laboratory biostratigraphic studies contribute to the final evaluation of wells, critical decisions are to be taken during drilling operations. Such decisions are directly related to the results of the ongoing drilling operation and how the prognosis of the stratigraphy agrees with the actual situation. The application of biostratigraphy to solving wellsite drilling problems has been highlighted by Copestake (1993). Most commonly, variations occur between the prognosis and actual well stratigraphy. The employment of the services of a Paleontologist during drilling to provide real time biostratigraphic data is thus very important. When such biostratigraphic data is integrated with lithologic description, log signatures and seismic data, it provides a formidable data base in monitoring the drilling operations. Information supplied by the wellsite paleontologist includes the traditional functions of biostratigraphy such as age determination, fault/unconformity identification, paleoenvironmental analysis and formation characterization/fingerprinting. Biostratigraphic data are also invaluable in well correlation and sequence stratigraphic studies. Giwa et al. (2006) stressed the use of biostratigraphy as providing a framework for correlating Maximum Flooding Surfaces and determining facies associations with the option of biosteering being explored. Biosteering (usually in conjunction with geosteering) is intended to maximize reservoir penetration by biostratigraphically "fingerprinting" the reservoir, enveloping non-pay stratigraphic units during drilling (Marshall and Nairn, 2005; Shipp and Marshall, 1995).

Three main microfossil groups namely: foraminifera, calcareous nannofossils and palynomorphs are commonly employed in wellsite biostratigraphic work. The fossil group employed at the wellsite depends on the kind of geological problems envisaged at the drilling site (well/field). In marine areas where paleobathymetry data is required, foraminifera will serve the purpose and provide clues to the age as well as structural interpretation. Palynological studies are efficient for paleoenvironmental interpretation and age determination of nearshore coastal sediments where foraminifera and nannofossils may be poorly distributed. Dinocysts in particular are useful in the marine environment. Nannofossils are the most precise fossil group for all age and structural interpretation in the deepwater marine environment.

Wellsite Calcareous nannofossil biostratigraphy has proved very useful in geological monitoring and minimizing correlation problems. The effectiveness of these exclusively marine fossils is enhanced by their short stratigraphic ranges resulting from the rapid evolutionary trends of many species. Resolution is thus of tens of thousands of years. This is further aided by the speedy processing technique that yields rapid results for real time age determination.

Experience in the use of local events in the Deep Offshore Niger Delta and the Gulf of Guinea has led to the subdivision of the entire

Neogene sequences into easily recognizable biostratigraphic units based on nannofossils (Fadiya, 2008; Fadiya and Salami, 2009).

In the Niger Delta, Benin/Dahomey Basin and the Joint Development Zone of Nigeria/Sao Tome and Principe offshore areas (Fig. 2), wellsite biostratigraphy has been applied in the age and geological monitoring of drilled sections. It has confirmed and modified stratigraphic prognosis and identified faults and unconformities. The technique has further been used for coring and casing point selection, confirming total depth where there is commitment to drill to sections of specified age, and confining wellbores within payzones through biosteering. Overpressured zones have also been easily identified within and across fields through the detection of observed biomarkers characterizing the sequence above the overpressured sequences.

Examples of geological problems solved in the three regions (Fig. 2) are discussed under the following headings:

(a) Age monitoring of well sections.
(b) Real time assessment versus predicted stratigraphy.
(c) Fault and unconformity identification.
(d) Correct stratigraphic positioning of casing points.
(e) Coring point selection, and
(f) Reservoir characterization/fingerprinting and Biosteering.

2. Wellsite biostratigraphy procedures

Reliable results were obtained by following the standard procedure and taking great care thereby aiding meaningful contribution to the critical decisions been taken at the drilling site.

Procedure:

- Samples are prepared in a mini-laboratory in the mud logging unit.
- Samples are taken from those prepared for the geologist for lithological examination. In many cases, samples are personally collected from the shaker. In fact, this is done more often as the 'sample catchers' tend to collect a single sample and split it into two sample depths especially when drilling is very fast. It is also possible for sample trays not to be properly cleaned. When the latter happens, sample analysis would give the impression that drilling is still through a single biostratigraphic zone when deeper zones have already been penetrated.

Fig. 2. Map showing the three studied oil prolific regions offshore Nigeria.

- Stages of work such as casing shoes and bottoms' up are recorded.
- The logs are studied to record areas of washout (as seen in the caliper logs)
- Cuttings from cavings are examined and their depths recorded.
- Lithological descriptions of the samples are undertaken to aid the interpretation.

2.1. Wellsite sample preparation and precautions

Precautions are taken during sample preparation on the rig as with normal laboratory biostratigraphic studies. One must avoid sample mix-up and protect the workspace to avoid interference from other workers. Wellsite nannofossil biostratigraphy is carried out with utmost care as samples can easily get contaminated with just a drop of water. Sieves for use in foraminiferal studies are cleaned properly before and after each sample preparation.

2.2. Analysis and interpretation

Prepared slides are arranged in the slide tray and analyzed in an office on the rig, which has minimum vibration. Depending on fossil group, different microscopes are used. Nannofossil studies require a polarizing microscope, foraminifera – a stereobinocular microscope and a light microscope for palynological studies. A camera attachment to the microscope for microphotographs of index taxa was found to be very helpful for reference purposes.

A detailed identification of all encountered fossils are usually made to species level and recorded in the logging (analysis) sheet. The logging sheet contains a column for the species identified and the abundance. Another column is available for notes on each sample analyzed including the state of preservation of the fossils.

Usually, abundance, diversity, and distribution plots are made with a fast and effective software e.g., Bugwin2K (Fig. 3). This allows a graphic understanding to both biostratigraphers and non-biostratigraphers in the exploration team who will make use of the data.

3. Wellsite biostratigraphy application in the Nigerian deepwater region

A combination of one or more of the under listed applications have been employed in wellsite drilling operations in the Niger Delta to proffer solution to geological problems at the well locations. The techniques have proved very useful as real-time data from the paleontologist are utilized by the drilling team. The attendant rapid turn-around time, which otherwise, could have been long, due to shipping and waiting time for laboratory analysis, aids the drilling process by providing a cost effective operation.

3.1. Age monitoring of well sections

Ages of penetrated sequences are monitored with the aid of calibrated bioevents whose 'Tops' {Last Appearance Datum (LAD)/ First Downhole Occurrence (FDO)} and 'Bases' {First Appearance Datum (FAD)/Last Downhole Occurrence (LDO)} have been established. In this way, the age of the encountered sequences are supplied to the geological team as drilling progresses. The supplied age from the bioevents provides useful tie points for correlation work. This is aided by the fauna and floral zones subdivided in the section by using their age limits. Age dating and biozonation are the basis on which every other biostratigraphic interpretations are based. Dating is based on the fact that one microfossil group or another constitutes very good index fossils in every part of the Geologic Column. Once sequences are dated and zoned, the relationship of

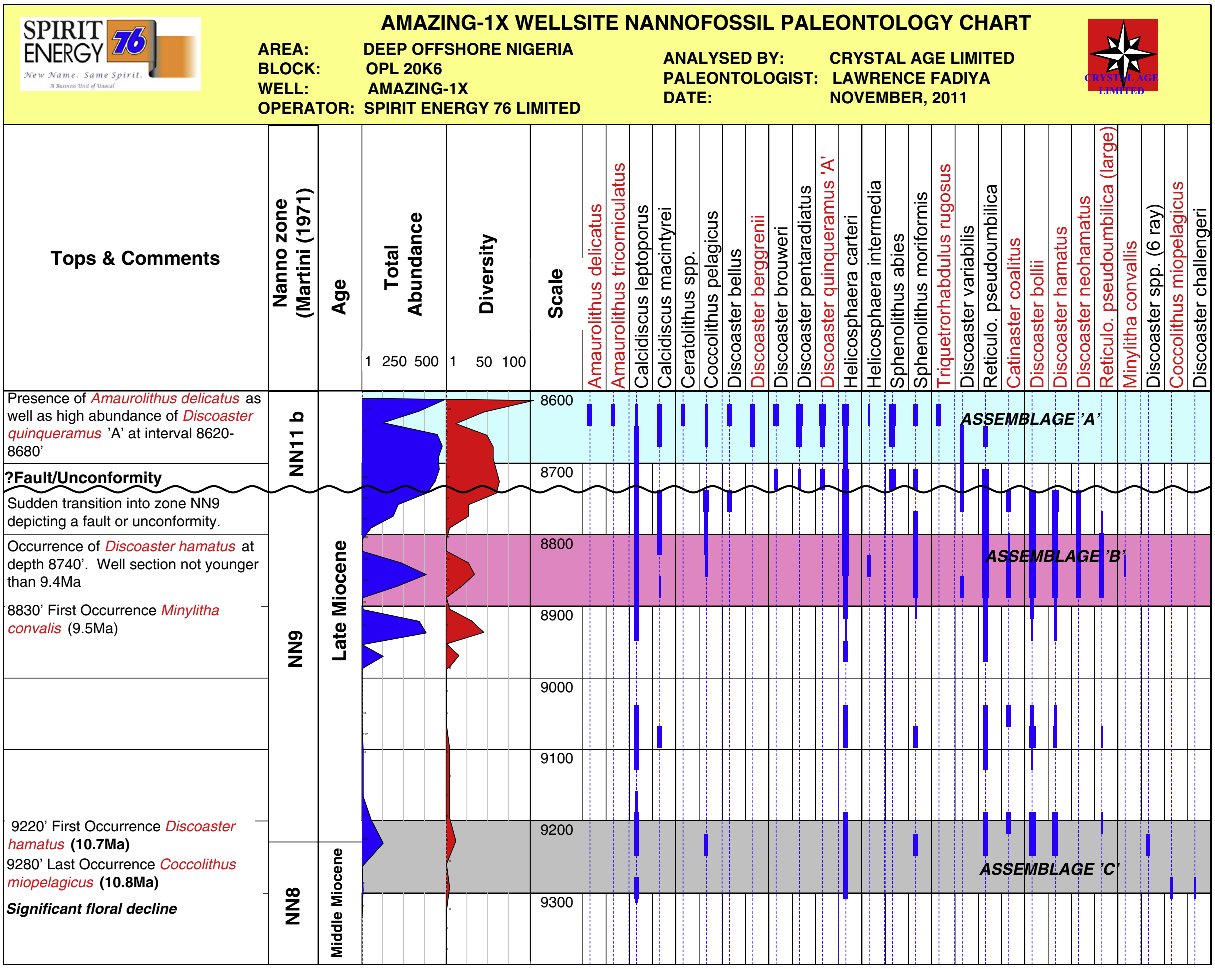

Fig. 3. A sample of wellsite nannofossil distribution chart using Bugwin2K software.

the encountered strata can be deduced (Simmons and Lowe, 1996). This technique has been applied in all the wellsite biostratigraphic work carried out in the Nigerian offshore region. With the dated bioevents and sequences penetrated subdivided into zones, a control is established over the drilled well sections. With the age and zones of the drilled section provided, a reliable correlation is made between the sections of the ongoing well with the adjacent wells especially when a good biostratigraphic data has been acquired on the offset well. Fig. 4 shows the dated bioevents in a checklist ('Tops' in red cells and 'Bases' in blue cells). This is used to monitor the well section down the hole. The age range of the zones also helps in the monitoring of the drilled sections.

3.2. Real time assessment versus predicted well stratigraphy

Prior to the drilling of the wells, a careful study of the geology of the area is made by the geological team. Seismic data acquisitions as well as interpretations are made with the target horizons clearly spelt out. The relevance of age to oil exploration again comes into limelight. A prognosis is made in which predictions of the target horizons are indicated. Reservoirs are code-named and corresponding Sequence Boundaries are dated from the seismic interpretations. In areas where structures such as faults or unconformity have been mapped, the depths at which such structures will be encountered are predicted. It is important that a deviation from the predicted depth is minimized so as to keep up with the planned well program. However, variations do occur in the prognosis as a result of some kind of error or misinterpretation regarding the depth to structures and targets. It is also believed that an integration of the different disciplines will produce the required high resolution for a successful drilling campaign. The drilling team counts on the biostratigrapher on the drilling rig, to give a real time assessment of the stratigraphy (actual) in relation to that in the prognosis.

A prognosis detailing the casing points, age and horizon tops and other information (Fig. 5a) is prepared as predicted from the seismic interpretation and other available data. However, an alternative table showing the actual stratigraphy as encountered while drilling (Fig. 5b) is prepared to confirm the prognosis or, for it to be updated from the real time biostratigraphy data. In situations where there is a wide gap between the predicted and actual stratigraphy, adjustments are made to the drilling program. Programs such as casing could be moved up or down depending on the confirmation of prognosed horizon thickness and depths to targets.

3.3. Fault and unconformity identification

On the successful dating and zoning of the sequences in the well, wellsite biostratigraphy has aided in the identification of repeated and missing sections in many wells in the Nigerian deepwater areas. Some of these were picked earlier on seismic lines while many faults and unconformities were not noticed probably as a result of poor data quality or interpretational error. In either case, biostratigraphy has helped in confirming those noticed on

WELLSITE PALEONTOLOGY (CALCAREOUS NANNOFOSSIL) CHECKLIST WELL: AMAZING-2 NIGERIA DEEP WATER OPL YK3 DATE: DEC. 2011 CLIENT: SPIRIT ENERGY NIGERIA LIMITED PALEONTOLOGIST: LAWRENCE FADIYA (CRYSTAL AGE LIMITED)																							
sample depth (m)	Sphenolithus abies	Reticulofenestra pseudoumbilicu	Helicosphaera carteri	Calcidiscus macintyre	Discoaster pentaradiatus	Discoaster quinqueramus	Discoaster berggrenii	Coccolithus pelagicus	Discoaster variabilis	Reticulofenestra minuta	Reticulofenestra rotaria	Discoaster triradiatus	Pontosphaera multipora	Minylitha convalis	Catinaster mexicanus	Discoaster loeblichii	Discoaster neohamatus	Discoaster bollii	Discoaster hamatus	R. pseudoumbilicus (large)	Syracosphaera pulchra	Age/Nanno Zone	COMMENTS (Age in Ma)
3519	320	18	23	4	15	126	10	17	16													Late Miocene / NN11a	High abundance and diversity of nannofossils over interval 3519 - 3618m. This is believed to be associated with the 7.0Ma Maximum Flooding Surface (Haq et al., 1987) with the top of *Reticulofenestra rotaria* (7.0Ma) at depth 3555m. Top *Minylitha convalis* and *Catinaster mexicanus* (7.8Ma) at depth 3582m Base *D. berggrenii/quinqueramus* (8.6Ma) at depth 3645m
3528	89	3	24	1	4	7	68	5															
3537	22	4	3		2	5	38		4														
3546	8	14	15			5	8		2														
3555	125	62	84	4	4	45	253	27		28	1	1											
3564	235	74	187	5	4	44	433	20		29	1												
3573	322	84	282	6	2	40	662	28		36	1		1										
3582	600	135	320		5	17	751	29	26			4	5	1	7								
3591	16	7	9			2	17	4	2							2							
3600	102		60	7	45	12	10	28	24				10	1	3		3						
3609	191	61	183		28		12	6	24	16		1	6			2	16						
3618	104	34	121	5			2		8	6					1		16						
3627						1	1																
3636							2																
3645	12	5				6	9		3														
3654	10	8	28														7	3				NN10 (Late Miocene)	Top *Discoaster bollii* (9.1Ma) at depth 3654m
3663	15	45	111	7				23									8	125	120			NN9 (Late Miocene)	Top *Discoaster hamatus* (9.4Ma) at depth 3663m. Condensed interval 3654 - 3699m believed to be associated with the 9.2Ma Maximum Flooding Surface of Haq et al., 1987.
3672	42	121	144	8				36	96				4	2			57	336	352	76			
3681		90	72	8					24				2	1			14	120	72	30			
3690	12	121	105	3					56				3				28	132	94	36			
3699		36	32	2				3	12	7							5	45	18	28			
3708	6	7	7						6	3							3	7	8	3			
3717	5	22	18		1			4										17	6	4	1		

Fig. 4. Nannofossil checklist showing bioevents and zones in age monitoring.

PROGNOSED

Amazing #1 OPL23YK PRE-DRILL

Well Top and Lithology Prognosis

CASING POINTS	HORIZON TOPS	TIME BELOW SEAFLOOR TVDssb (TWT-ms)	SEISMIC TIME BELOW SEALEVEL TVDss TWT-ms	DEPTH BELOW SEAFLOOR TVDssb (FT)	DEPTH BELOW SEALEVEL TVDss (FT)	WELL LOG MEASURED DEPTH RKB MD (FT)
	Seafloor	0	4320.5	0	3820	3906
36" csg		152.4	4533.6	232	4005	4138
	Pleistocene					
	1.6my event	183.7	4620.1	411	4235	4549
20" csg		266.8	4731.4	707	4785	5256
	2.2my event	285	4880	930	4992	6186
	Pliocene					
	Top 3.0 my Reservoir	365.6	5440	1061.2	5102	6224.2
	Top 3.8 my Reservoir	412.7	5604	1255	5463	6578.2
13 3/8" csg		500.2	5710	1502.3	5642	6755.5
	Top 4.2 my Reservoir	521.5	5766	1564	5680	6986.5
	Miocene					
	Top 5.5 my Reservoir	580.2	5903	1843.1	6234	7548.4
	Top 6.3 my Reservoir	663	6123	2445.3	6654	7995.7
	Top 8.2 my Reservoir	920.2	6500	2964.6	7145	8454.4
	Top 10.5 my Reservoir	1445.7	6867	3356.9	7664	9001
9 5/8" csg	TD	2654.6	9564	4722	8578	10438

Fig. 5a. A seismic prognosis for a proposed well with ages, tops of prospects and expected depths of sequence boundaries.

ACTUAL

Amazing #1 OPL23YK PRE-DRILL

Well Top and Lithology Prognosis

CASING POINTS	HORIZON TOPS	TIME BELOW SEAFLOOR TVDssb (TWT-ms)	SEISMIC: TIME BELOW SEALEVEL TVDss TWT-ms	DEPTH BELOW SEAFLOOR TVDssb (FT)	DEPTH BELOW SEALEVEL TVDss (FT)	WELL LOG: MEASURED DEPTH RKB MD (FT)
	Seafloor	0	4320.5	0	3820	3906
36" csg		152.4		232	4005	4138
	Pleistocene					
	1.6my event	183.7		411	4235	4549
20" csg		266.8		707	4785	5256
	2.2my event	285		930	4992	6186
	Pliocene					
	Top 3.0 my Reservoir	365.6		1061.2	5102	6224.2
	Top 3.8 my Reservoir	412.7		1255	5463	6578.2
13 3/8" csg		500.2		1502.3	5642	6755.5
	Top 4.2 my Reservoir	521.5		1564	5680	6986.5
	Miocene					
	Top 5.5 my Reservoir	580.2		1843.1	6234	7548.4
	Top 6.3 my Reservoir	663		2445.3	6654	7995.7
	Top 8.2 my Reservoir	920.2		2964.6	7145	8454.4
	Top 10.5 my Reservoir	1445.7		3356.9	7664	9001
9 5/8" csg	TD	2654.6		4722	8578	10438

*PRELIMINARY VALUES TO BE UPDATED BY BIOSTRAT ANALYSIS

Fig. 5b. Actual 'Tops' of sequences: to be filled in as drilling progresses and confirmed by biostratigraphic analyses.

seismic section with the actual depth picked while those not observed on seismic section were also picked outright at the wellsite. Fig. 6a shows a well section penetrating biozones G, H1, H2, H3, H4, I and J while a repetition of zones H4 and I was noticed. It is expected that the sequence becomes older rather than younger. It therefore becomes obvious that a faulted section is encountered. In the example shown, a reverse fault is indicated by the repeated section.

Missing sections are characteristics of normal faults. The identification of a fault or an unconformity is vital in exploration to identify potential traps. One can also find out if the reservoir has been eroded due to unconformity or if the reservoir is repeated in case of a faulted section. Fig. 6b shows an example of a well penetrating through an unconformity. It shows that zones U, V, and W were completely eroded prior to the deposition of sequences R, S, and T even though the well seems to penetrate an undisturbed sequence. Faults and unconformities are common phenomenon

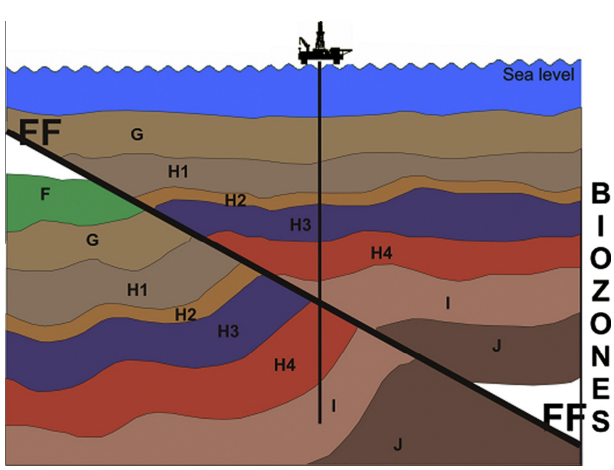

Fig. 6a. Thrust fault identified from biostratigraphic analysis: repeated strata indicated by the reappearance of zones H4 and I.

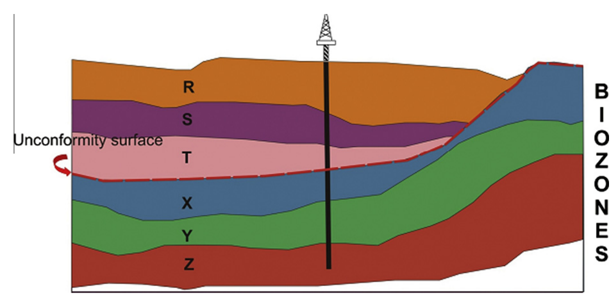

Fig. 6b. Unconformity identification from biostratigraphic analysis. Missing sections indicated by the absence of zones U, V, and W.

in the deepwater areas of the three (3) Nigerian offshore areas shown in Fig. 2.

In cases where missing sections were noticed from the biostratigraphic data, a quick re-look at the seismic section (if available), commonly gives a confirmation. Further confirmation are normally made by looking at some possible evidences of slickensides from ditch cuttings or cavings around the fault. Clays generated from the heat of moving blocks on fault surfaces are often noticeable in the cuttings. Unconformities can be confirmed by the presence of some ferruginous materials in the ditch cuttings when examined under the binocular microscope. These clues have proved effective in the confirmation of identified faults and unconformities during drilling in many wells in the Niger Delta deepwater areas.

3.4. Correct stratigraphic positioning of casing points

A planned program may put casing points in the shale of a particular age, e.g., in a shale unit below the 12.5 Ma Sequence Boundary. This will easily be located using the biostrati-graphic data. Real time data supplies the age of encountered horizons and this will be provided through the age monitoring of the drilled sections. For appraisal wells, successful casing point of the exploratory wells are easily correlated using both the age and zones of the sequences.

For casing above an overpressured zone in an offshore Niger Delta well, the zone is heralded by the First Downhole Occurrence of *Sphenolithus belemnos*. Once the top of this fossil is picked, a quick decision to case the well is made. Consequently, other preventive measures to keep drilling safe in an overpressured situation were put in place. Several wells with overpressured horizons have been drilled successfully in this way with different fossils used as indicators in different fields and blocks. Many reservoirs horizons were found below such overpressured zones.

3.5. Coring point selection

Coring points are commonly defined in the well proposal and/or well program. Estimated depths are indicated in the prognosis but care must be taken to select the point to stop for coring. This is important so as not to drill out the objective or miss it by coring the 'gangue'. In coring a thin objective, this must be done as precise as possible. Missing the objective has serious cost implications as coring programs are very expensive.

Several methods are used to pick coring points but an integration of all of them is advisable. Coring points can be picked by establishing a correlation point between the ROP (rate of penetration) plot of the well and that of adjacent wells. The ROP can be correlated to the GR, SP or sonic logs. Whatever makes a reliable correlation is used and the coring point can be picked. Drilling breaks are effective method of picking coring points in clastic sedimentary sections. The drilling break is easily noticed during a sudden transition into softer or harder formation. The 'Drilling Break' approach must be used with care as the sand sequence responsible for the break may not be the desired objective. The 'bottoms-up-and-see' approach also has a cost implication considering the time (at least one hour) involved in circulating bottoms-up. This is very expensive when related to rig time and rig cost.

Practical experiences in the Niger Delta has shown that, a combination of drilling breaks and biostratigraphic data from wellsite paleontologist provides an accurate and effective clue to coring point selection while the time involved in circulating bottoms up is saved. This is because the biostratigraphic data helps build the confidence in correlation and there is no need for circulating the bottoms up.

With well-zoned, dated and fingerprinted stratigraphic units, coring point determination is easy. This is basically a correlation work. In the wildcat, the biostratigrapher identifies the shale above the reservoir and moves further to subdivide it noting the size, shape and the behavior of the fossils that characterizes the unit. In this way he is able to look at the fossils behavior especially when drilling is close to the reservoir of interest, hence, the zone of interest is cored. Note that the wellsite biostratigrapher does not solely decide on when to stop for coring but the biostratigraphic data supplied is 'crucial' to picking the coring point by the drilling team.

3.5.1. Experiences in coring point selection

One of the major operations in an appraisal well is coring, though this is also done sometimes in wildcats depending on the drilling program. In a coring operation in the deepwater Niger Delta, the objective has been identified in the exploratory well AC-1 (Fig. 7a), while the task is to core the same objective in well AC-2 which is currently being drilled. The biostratigrapher was employed purposely to ensure accurate coring point selection. Gamma Ray and Resistivity logs as well as ROP curve correlation produced the correlation in Fig. 7a prior to integration with biostratigraphic data. The tentative coring point selected is marked 'X'. Integrating these with biostratigraphic data (dated bioevents and abundance and diversity curves) showed the actual coring point for the desired objective to be below the one marked 'X' earlier (Fig. 7b). A re-evaluation of all available data enabled a successful coring point selection (Fig. 7c). In practice, this is faster as all the data are integrated in 'real-time'.

3.6. Reservoir characterization and biosteering

Using an erected biostratigraphic scheme (from work experience in the Nigerian deep offshore areas) as a framework, reservoirs are easily differentiated based on the fossil content from the unit above and below. A deviation from formal or 'global' biozonation comes into play here as consistent local events are used in developing a localized field-focused scheme - a method suggested by Payne et al. (1999). This implies that the reservoir is identified by the fossils that are peculiar to the unit only or to those above and below it. In cases where the reservoir is either thin or does not occupy the whole unit, the reservoir can be placed somewhere on the top, center or bottom of the subunits. This can be made

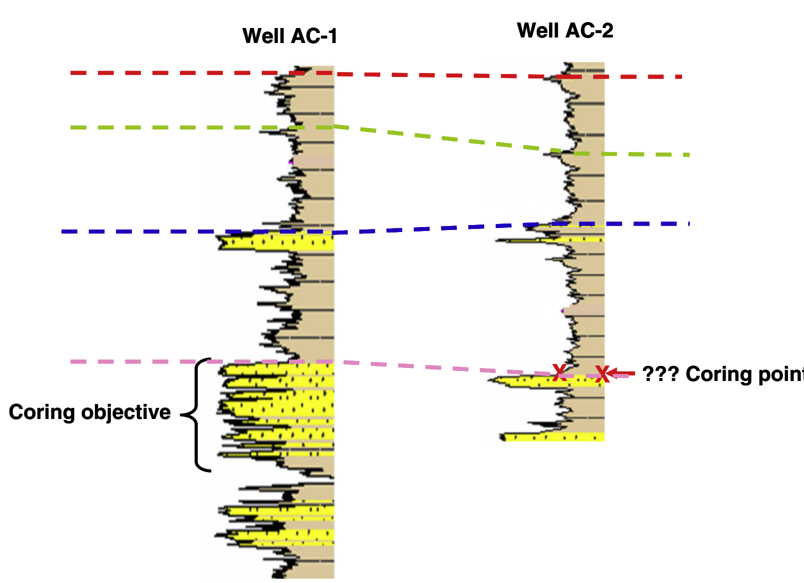

Fig. 7a. Visual correlation from logs before biostratigraphy data.

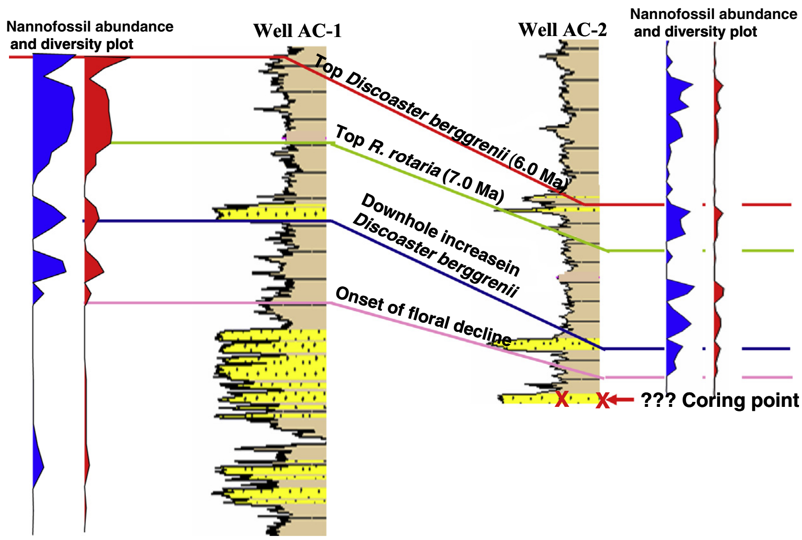

Fig. 7b. Integration of available information with biostratigraphic data.

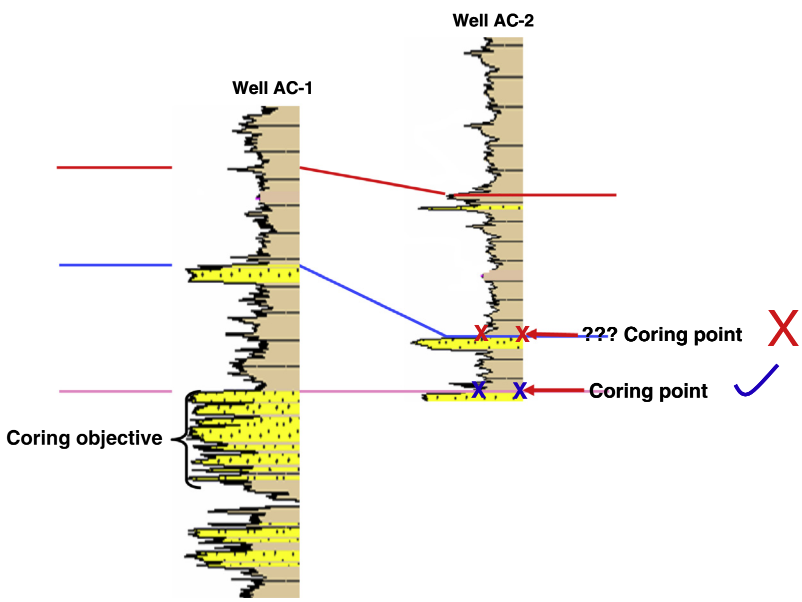

Fig. 7c. Final integration and true coring point picked.

possible by studying the behavioral changes in size, shape and abundance of the characteristic fossils of the subunit.

Instances were also recorded where the shale above the reservoir is characterized by an assemblage of fossils which is unique to it while the shale below is characterized by another unique fossil assemblage. The reservoir itself may be barren entirely and

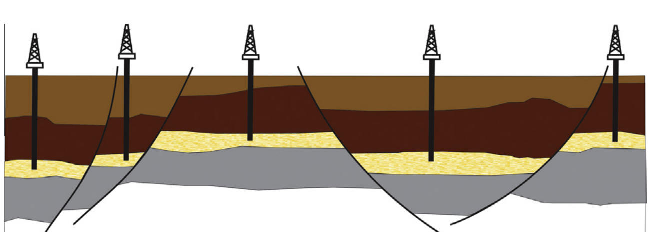

Fig. 8a. Producing from a thin reservoir through multiple wells – expensive option A.

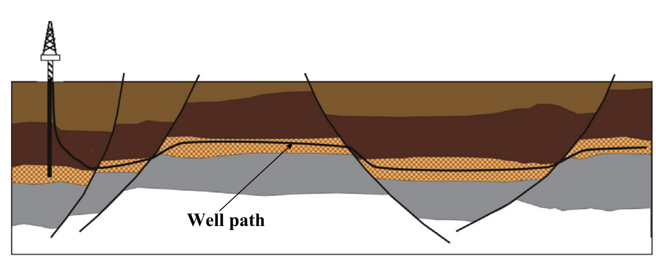

Fig. 8b. Producing from a thin reservoir through a single wells – economical option B.

sandwiched between the fossiliferous shale units. When reservoirs are identified by their unique fossil content or differentiated from the sequences above and below as explained above, biosteering is made easy as the reservoir can be identified as long as the drilling bit remains within the reservoir. When the drilling bit goes into

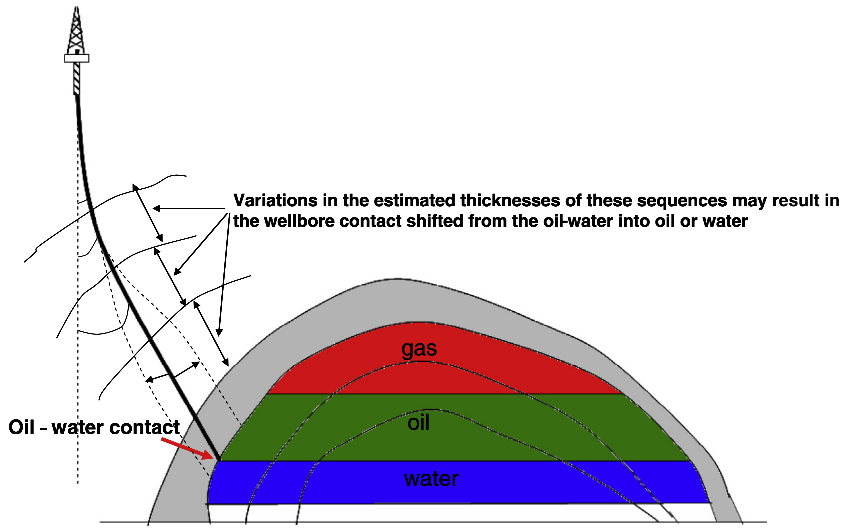

Fig. 8c. Biosteering of well bore to penetrate reservoir at the oil–water contact.

another sequence, the biostratigrapher identifies this and directs the driller which way to go.

3.6.1. Experience in biosteering

Experience of biosteering in the Niger Delta deepwater region covers a variety of applications to aid exploration and production. Piloting horizontal wells is on one part. Production economics is aided by producing from a thin, faulted reservoir through just one well rather than many wells penetrating the same sectionalized reservoir. For instance, Fig. 8a shows the drilling of 5 wells to produce the oil from the thin reservoir at a high cost of drilling while Fig. 8b shows a single horizontally drilled well to produce from the same reservoir at a cheaper cost. This is made possible by biosteering a single well and ensuring maximum penetration of the reservoir.

Biosteering is enhanced by fingerprinting the cap (shale) and seal (shale) of the reservoir. The drilling bit is then piloted and maintained within the reservoir. If the fossil assemblage characterizing the cap rock is encountered, the biostratigrapher directs the driller to go down. When the fossil assemblage characterizing the seal is encountered, the driller will move up to keep the well path within the reservoir. In faulted sequences where there is a relative movement of the reservoir, biosteering still assists in piloting the wellbore to the desired objective.

In two instances of drilling an appraisal and a production well, wellbores were targeted at intersecting the oil–water contact or gas-oil contact probably for reserve estimation or water injection or simply production purposes. Biostratigraphy played a big role in piloting the wellbore. The code-named sequences (horizon units) have estimated thicknesses from seismic prognosis but these were found to vary (either thicker or thinner) in most cases on confirmation from biostratigraphic data (Fig. 8c). The directional drillers who already had in their program the deviation angles at different depths had to adjust the angles on the confirmation of actual thicknesses of the encountered units. With proper monitoring of the beds thickness, the wellbore was successfully piloted to intersect the oil–water contact as targeted in the drilling program.

4. Conclusion

'Real-time' wellsite biostratigraphic analysis on Nigerian deepwater wells provides precise stratigraphic control while drilling. This has been achieved through rapid, high precision age dating of successions of strata. Fingerprinting of penetrated sedimentary successions enabled the subdivision of sequences into easily recognizable and correlatable units. Interpretations of the biostratigraphic results on location have been very useful in the reconstructing of the subsurface geology, planning of well paths, recognition of hiatuses, decision making during drilling and maximizing hydrocarbon recovery. Expensive offshore rig time and cost is avoided through accurate location of casing depths, coring points and terminal depth. 'Getting it right at first' has helped in avoiding drilling expensive sidetracks. Precise stratigraphic monitoring has helped avoid overpressured shales and consequently saved personnel life as well as the drilling rigs. The contribution of wellsite biostratigraphy has added a lot of value to exploration drilling in the deepwater Niger Delta and more importantly in the toe thrust belt with complex subsurface structural geological uncertainty. Operators have been delighted at the success of the technique even though many were reluctant to use it at the beginning of their drilling campaign.

Acknowledgements

I thank Chevron Nigeria Limited, Ocean Energy Nigeria Limited, Petroleo Brasileiro Nigeria Limited, Statoil Nigeria Limited and other Nigerian deepwater operators for offering Crystal Age Limited the opportunity to render wellsite biostratigraphic services. I am also grateful to the Management and Wellsite biostratigraphy team of Crystal Age Limited who permitted the sharing of this information from their immense data base. I am grateful to Professors M.B. Salami and M.O. Odebode for their invaluable contributions to my training as a micropaleontologist.

References

Ajakaiye, D.E., Bally, A.W., 2002. Some structural styles on reflection profiles from Offshore Niger Delta. Search and Discovery Article #10031.

Copestake, P., 1993. Application of micropaleontology to hydrocarbon exploration in the North Sea basin. In: Jenkins, D.G. (Ed.), Applied Micropaleontology. Kluwer Academic Publishers, Netherlands, pp. 93–152.

Corredor, F., Shaw, J.H., Bilotti, F., 2005. Structural styles in the deep-water fold and thrust belts of the Niger Delta. Am. Assoc. Petrol. Geol. Bull. 89, 753–780.

Fadiya, S.L., 2008. Calcareous Nannofossil Biozonation Scheme for the Deep Offshore Niger Delta. Unpublished Ph.D. Thesis, Department of Geology, Obafemi Awolowo University, Ile-Ife, Nigeria, pp. 244.

Fadiya, S.L., Salami, M.B., 2009. A Neogene calcareous Nannofossil Biozonation Scheme for the Deep Offshore Niger Delta. In: A Paper Presented at the Nigerian Association of Petroleum Explorationists' 27th International Conference and Exhibitions, Abuja, Nigeria.

Giwa, G.O., Oyede, A.C., Okosun, E.A., 2006. Advances in the Application of Biostratigraphy to Petroleum Exploration and Production. Search and Discovery Article #50029.

Leduc, A.M., Davies, R.J., Densmore, L.A., Imber, J., 2012. The lateral strike-slip domain in gravitational detachment delta systems: A case study of the northwestern margin of the Niger Delta. Am. Assoc. Petrol. Geol. Bull. 96, 709–728.

Maloney, D., Davies, R., Imber, J., Higgins, S., King, S., 2010. New insights into deformation mechanisms in the gravitationally driven Niger Delta deep-water fold and thrust belt. Am. Assoc. Petrol. Geol. Bull. 94, 1401–1424.

Marshall, P.R., Nairn, E.A., 2005. Developments in Biosteering Techniques and their Application to Solving Reservoir Scale, Subsurface Geological/Geophysical Problems. Geologic Problem Solving with Microfossils Conference Abstract Volume with Program. North American Micropaleontology Section Publication (International Conference in Memory of Gary D. Jones, Rice University, Houston, Texas, USA).

Payne, S.N.J., Ewen, D.F., Bowman, M.J. 1999. The role and value of 'high-impact biostratigraphy' in reservoir appraisal and development. In Jones, R.W., Simmons, M.D., Simmons, (Eds.), Biostratigraphy in production and development geology, Geological Society Special Publication 152, pp. 5–22.

Ramirez, R., Rodriguez, O.M.V., Zambrano, D.A.S., 2005. Biostratigraphy Impact in the Geology Study during Exploration Drilling, Northwest Monagas Oilfields, Eastern Venezuelan Basin. Geologic Problem Solving with Microfossils Conference Abstract Volume with Program. North American Micropaleontology Section Publication (International Conference in Memory of Gary D. Jones, Rice University, Houston, Texas, USA).

Shipp, D.J., Marshall, P.R., 1995. Biostratigraphic steering of horizontal wells. In: Al-Husseini, M.I. (Ed.), Geo '94 Middle East Petroleum Geoscience. Gulf Petrolink, Bahrain, pp. 849–860.

Simmons, M.D., Lowe, S., 1996. The future of paleontology? an industrial perspective. Geoscientist 6, 14–16.